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Thermodynamic Limitations on Energy Conversion in Laser Propulsion

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10th International Workshop on Combustion and Propulsion
IN-SPACE PROPULSION
21-25 September 2003
Lerici, La Spezia, Italy

Outline

Tour of White Sands Laboratory (HELSTF/PLVTS) and Video of Flight Testing.

Comparison of Constant Momentum Mission and Constant Specific Impulse Mission. Δv, v_{jet}, f, m_o, v_o, P_{jet}, m/E_{jet}

Efficiency of conversion of laser energy to propellant kinetic energy, $\alpha\beta$.

Upper limit to conversion of laser energy to jet kinetic energy from energy conservation and definitions: $Cv_{jet} = \alpha\beta\Phi < 1$.

Comparing momentum quantities to energy quantities. The "Phi Factor" $\Phi = \langle v\rangle^2/\langle v^2\rangle$ and velocity distributions in propellant jet. Φ values for delta function, Maxwellian, Gaussian, Chunks and gas, supersonic expansion, etc.

Upper limits to performance based on chemical thermodynamics. Blowdown from defined equilibrium state (u, ρ) of known volume.

Conclusions

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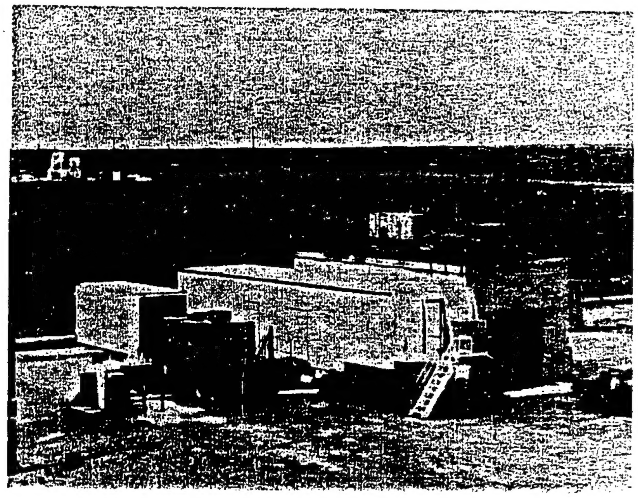
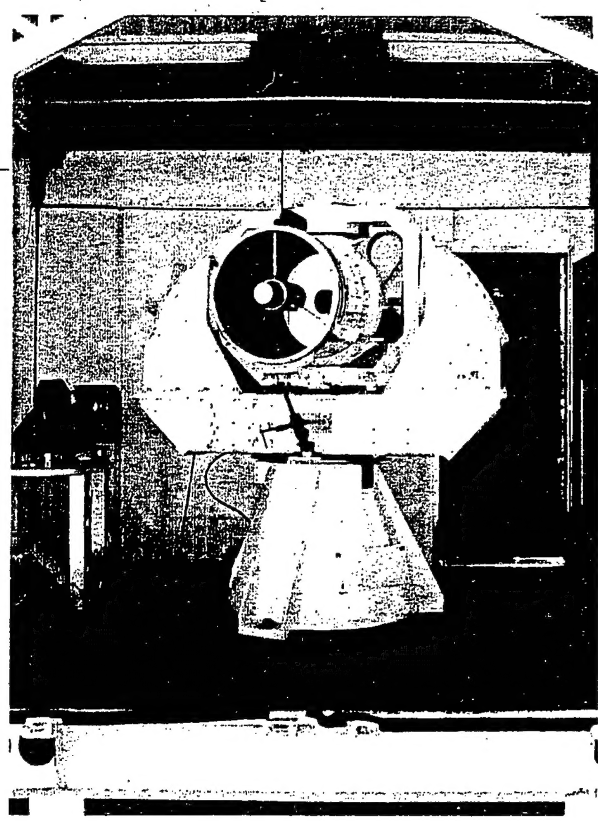
Pulsed Laser Vulnerability Test System (PLVTS)

- Original Performance
  - 800 joules/pulse
  - 10 Hz
  - 30μsec pulses
- Modified Performance
  - 1998
    - 400 joules/pulse
    - 28 Hz
    - 18μsec pulses
  - 1999
    - 150 joules/pulse
    - 30 Hz
    - 5μsec pulses

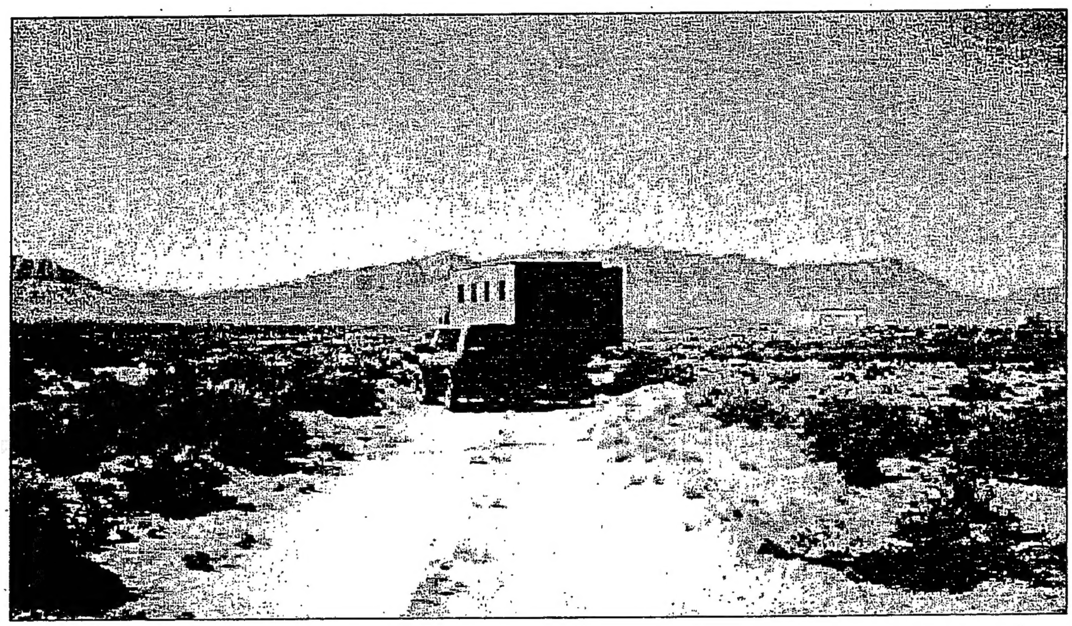


Field Test Telescope (FTT)
- 50 cm
- Cassegrainian
- Dynamic Focusing
- Minimum Acquisition Distance is 200 m

Laser Beam Handoff to This Telescope Should Allow Altitudes of ~300 m (1,000 ft)



Optical Bench Set Up At 500-Ft Mark



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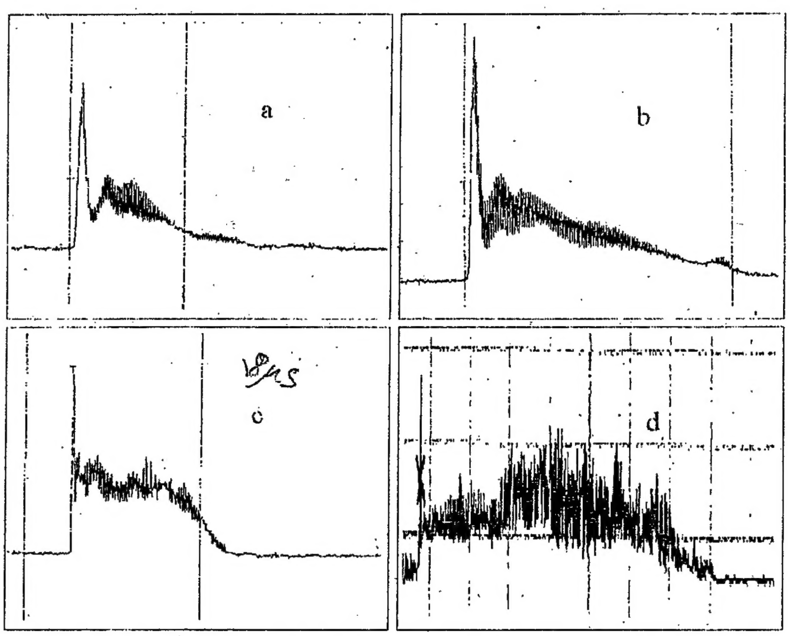
Optical Power vs Time: a) 2.5μs; b) 5μs; c) 18μs; d) 35μs



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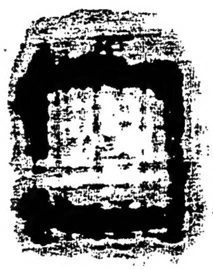
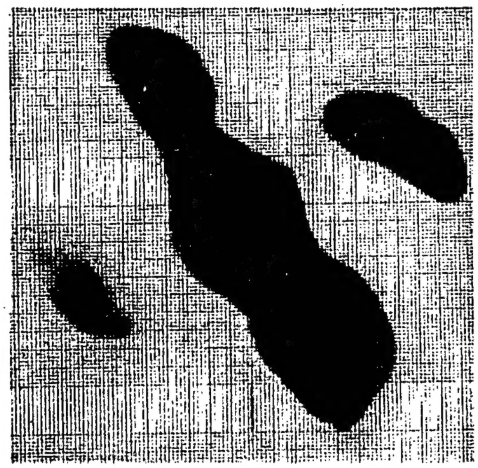
Laboratory Telescope Burn Patterns



Near Field
At ~10 Ft



5 cm Ref.

500 Ft

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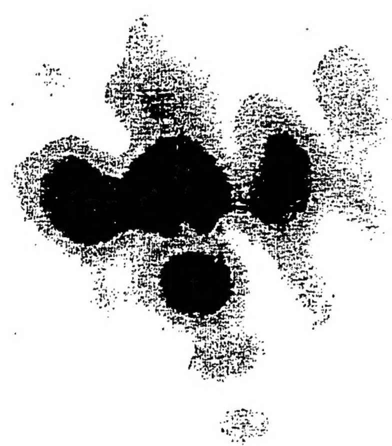
FTT Beam Burn Patterns

500 Ft

1,000 Ft



11 cm Ref.

1,500 Ft

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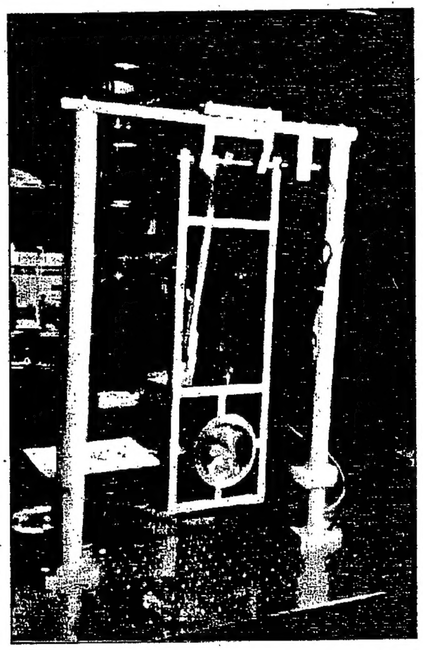
Pendulum Impulse Test Stand



Measure:
1. Impulse
2. Laser Energy
3. Mass ablated

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350 J / 25 cm² / 18 μS
14 J/cm²   0.8 MW/cm²

at 350 J.
m ~ 40 mg
~ 11 μm thick layer.

$\epsilon \lesssim 14$

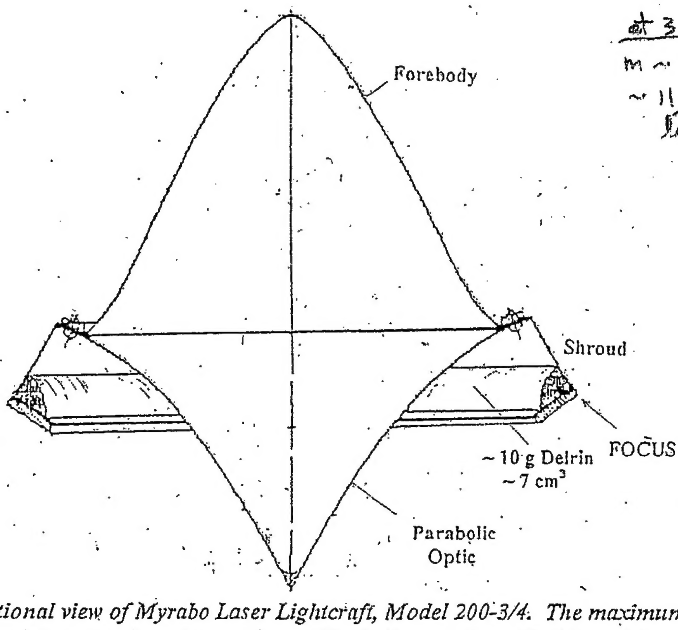

Figure 2. Cross-sectional view of Myrabo Laser Lightcraft, Model 200-3/4. The maximum diameter of the test article at the shroud is ~ 10 cm. The indicated ring of Delrin weighs ~ 10 g and has a volume of ~ 7 cm³ and a surface area ~ 25 cm². The idealized maximum plug nozzle exit area is ~ 350 cm².

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Overall Energy Conversion in Laser Propulsion Mission

$$E_f = \tfrac{1}{2}\, m_f v_f^2 = \eta\, \alpha\, \beta\, \gamma\, \delta\, E_{wall}$$

η = propulsion efficiency (jet kinetic energy to vehicle kinetic energy)

α = expansion efficiency (internal propellant energy to jet kinetic energy)

β = absorption efficiency (laser energy at vehicle to internal propellant energy)

γ = transmission efficiency (laser energy at ground to laser energy at vehicle)

δ = laser efficiency (electric energy to laser energy at ground)

***** **Issue: separability of $\eta\ \alpha\ \beta\ \gamma$** *****

" $500 worth of electricity to put 1 kg into LEO."

At $0.10/KWH, $500 buys 18,000MJ (1 KWH = 3.6 MJ); 1 kg at 10 km/s → E_f = 50 MJ, so $\eta\alpha\beta\gamma\delta \geq 0.0028$

Phipps, Reilly, Campbell, *Laser & Particle Beams* 18 (2001) 661-695
Pirri, Monsler, Nebolsine, *AIAA Journal* 12 (1974) 1254-1261

INSTANTANEOUS PROPULSION EFFICIENCY

$$\eta_i = \frac{2\,(v/v_{jet})}{1 + (v/v_{jet})^2}$$

CONSTANT MOMENTUM COMPARED TO CONSTANT SPECIFIC IMPULSE MISSION

The Constant Specific Impulse Mission

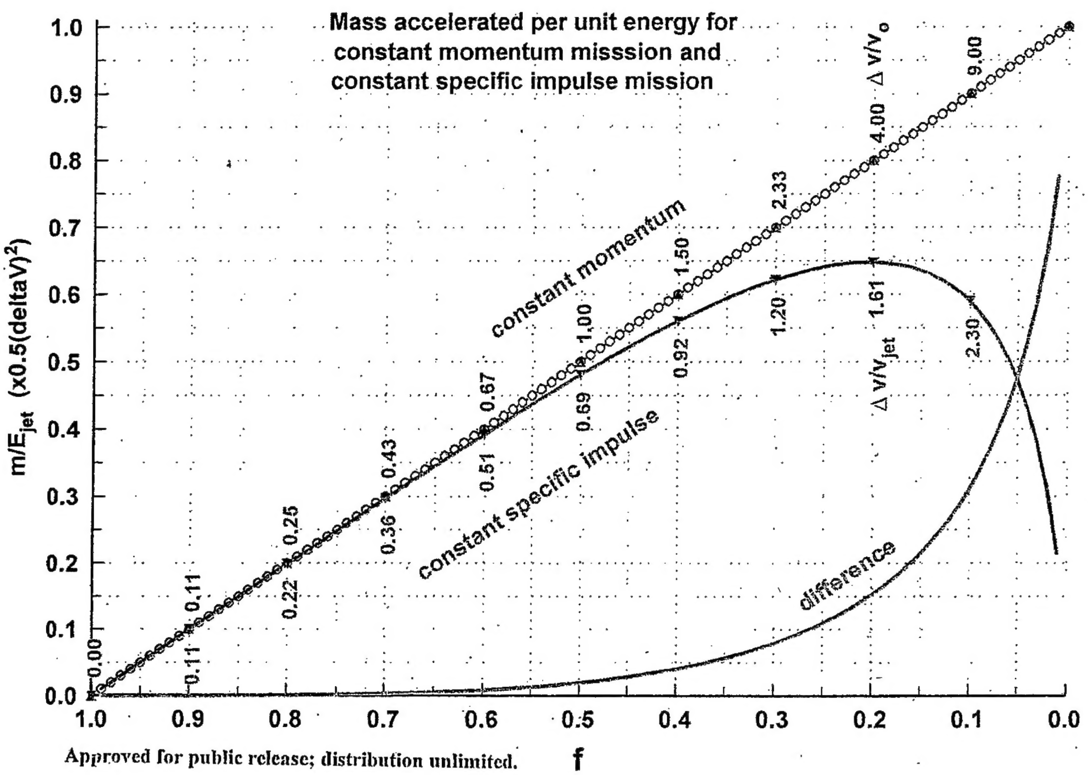
$$\int_{m_o}^{m} \frac{dm}{m} = \frac{-1}{v_{jet}} \int_{v_o}^{v} dv$$

$$f = \frac{m}{m_o} = \exp -\left(\frac{v - v_o}{v_{jet}}\right) = \exp \frac{-\Delta v}{v_{jet}}$$

The Constant Momentum Mission

$$\int_{m_o}^{m} \frac{dm}{m} = -\int_{v_o}^{v} \frac{dv}{v}$$

$$f' = \frac{m}{m_o} = \frac{v_o}{v} = 1 - \frac{\Delta v}{v} = \left(1 + \frac{\Delta v}{v_o}\right)^{-1}$$



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benefit3.axg July 29, 2003 9:11:47 AM

Figures of Merit for Laser Propulsion: m/E_{jet}

The Constant Specific Impulse Mission

$$E_{jet} = -\frac{1}{2}\int_{m_o}^{m} v_{jet}^2\,dm = \frac{1}{2}(m_o - m)v_{jet}^2$$

$$B = \frac{m}{\frac{1}{2}(m_o - m)\,v_{jet}^2} = \frac{2x^2}{(e^x - 1)[\Delta v]^2} = \frac{2f(\ln f)^2}{(1-f)[\Delta v]^2}$$

The Constant Momentum Mission

$$E'_{jet} = -\frac{1}{2}\int_{m_o}^{m} v^2\,dm = -\frac{1}{2}(m_o v_o)^2\int_{m_o}^{m}\frac{dm}{m^2} = \frac{1}{2}mv^2 - \frac{1}{2}m_o v_o^2 = \frac{1}{2}mv\Delta v$$

$$B' = \frac{m}{\frac{1}{2}mv\Delta v} = \frac{2(1-f')}{[\Delta v]^2}$$

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MISSION TIME FOR CONSTANT SPECIFIC IMPULSE AND CONSTANT MOMENTUM MISSIONS

Constant Specific Impulse

$$P_{jet} = \tfrac{1}{2} v_{jet}^2 \frac{dm}{dt} = \tfrac{1}{2} F v_{jet} \qquad f = \frac{m}{m_o} = 1 - \frac{2P_{jet}}{m_o v_{jet}^2} t \qquad t = \frac{m_o}{2P_{jet}} (\Delta v)^2 \frac{(1-f)}{(\ln f)^2}$$

$$\Delta v = -v_{jet} \ln\left(1 - \frac{2P_{jet}}{m_o v_{jet}^2} t\right) = \sqrt{\frac{2P_{jet}}{m_o} \frac{(\ln f)^2}{(1-f)} t} = \ln\left(\frac{BP_{jet}}{m_o} t\right) \sqrt{\frac{\frac{2P_{jet}}{m_o}}{\left(1 - \frac{BP_{jet}}{m_o} t\right)} t}$$

Constant Momentum

$$P_{jet} = \tfrac{1}{2} v^2 \frac{dm}{dt} = \tfrac{1}{2} F v \qquad f' = \frac{m}{m_o} = \left[1 + \frac{2P_{jet}}{m_o v_o^2} t'\right]^{-1} \qquad t' = \frac{m_o}{2P_{jet}} (\Delta' v)^2 \frac{f'}{(1-f')}$$

$$\Delta' v = \frac{2P_{jet}}{m_o v_o} t' = \sqrt{\frac{2P_{jet}}{m_o} \frac{(1-f')}{f'} t'} = \sqrt{\frac{2}{B'} \frac{2P_{jet}}{m_o} t'}$$

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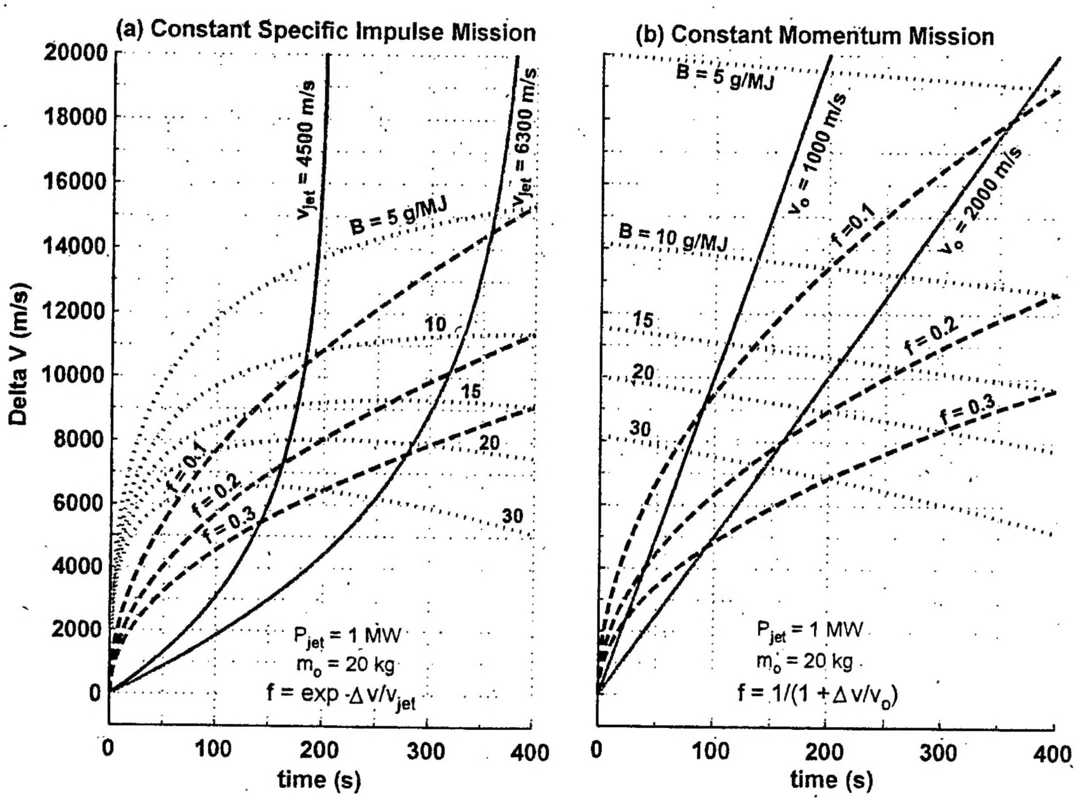

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Definitions and Energy Conservation

Propellant Kinetic Energy: $E_p = \frac{1}{2} m_p \langle v_e^2 \rangle = \alpha\beta\, E_L$ $\qquad \langle v_e^2 \rangle = \dfrac{\int_{\rho_c}^{\rho_f} d(\rho v_e^2)}{\int_{\rho_c}^{\rho_f} d\rho}$

Propellant Impulse: $I = m_p \langle v_e \rangle$ $\qquad \langle v_e \rangle = \dfrac{\int_{\rho_c}^{\rho_f} d(\rho v_e)}{\int_{\rho_c}^{\rho_f} d\rho}$

Coupling Coefficient: $C = \dfrac{I}{E_L}$ $\qquad C = \dfrac{2\alpha\beta}{\langle v_e \rangle}\left[\dfrac{\langle v_e \rangle^2}{\langle v_e^2 \rangle}\right] = \dfrac{2\alpha\beta\Phi}{\langle v_e \rangle}$

Energy Conservation: $\boxed{\alpha\beta\Phi = \dfrac{I^2}{2 m_p E_L}} = \dfrac{CI}{2 m_p} = \dfrac{C\langle v_e \rangle}{2} = \dfrac{I\langle v_e \rangle}{2 E_L} \le 1$

Propellant Internal Energy: $Q^* = u_c - u^o = \dfrac{\beta E_L}{m_p}$ $\qquad C = \dfrac{\beta \langle v_e \rangle}{u_c - u^o}$

Propellant with added chemical energy, Δu: $(\alpha\beta\Phi)_{apparent} = \alpha\Phi(\beta + m_p \Delta u / E_L)$

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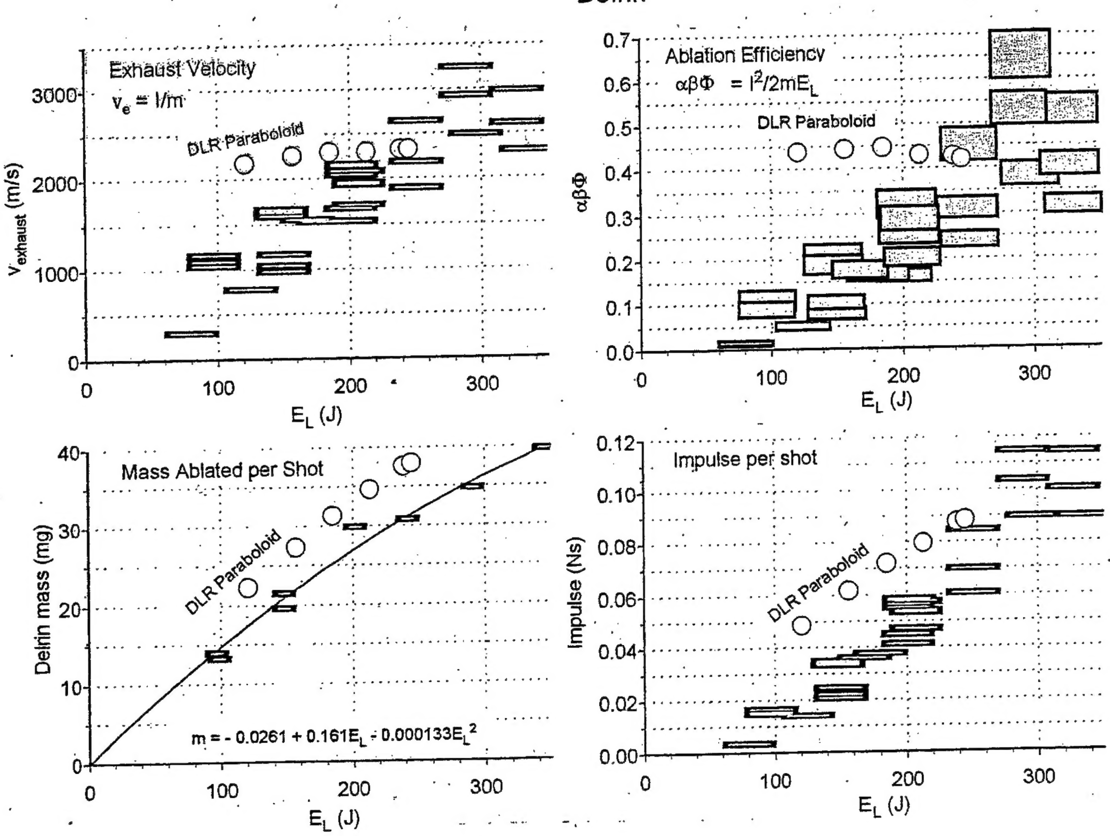
Delrin



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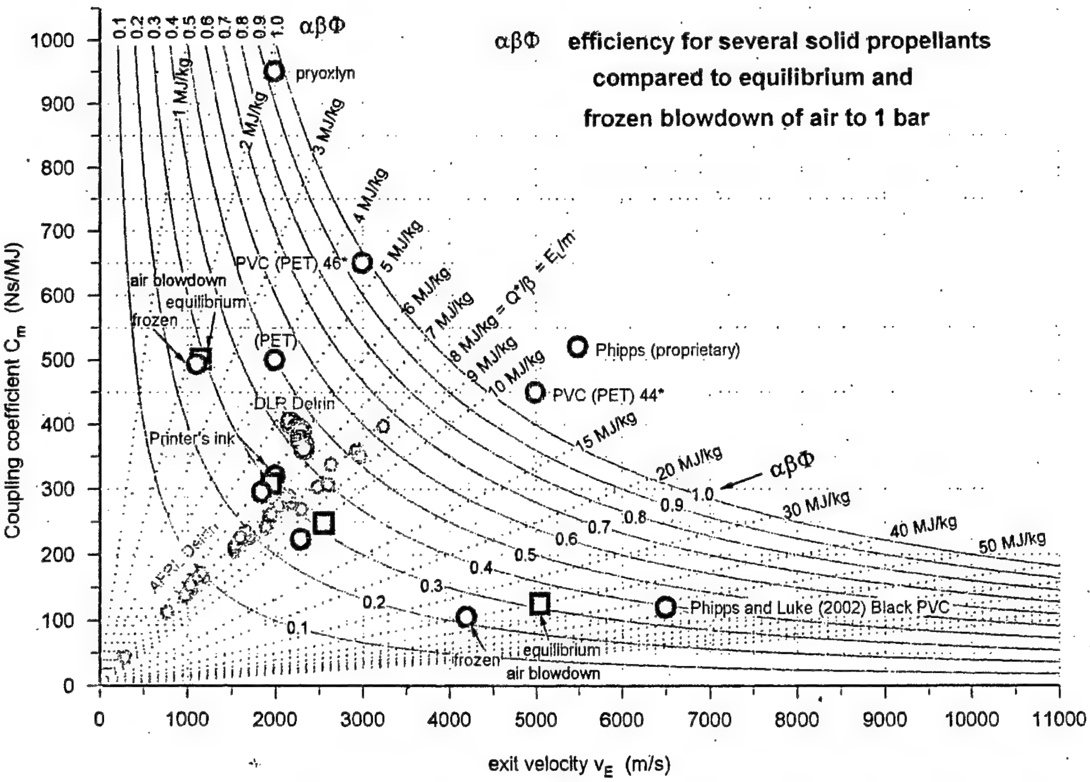

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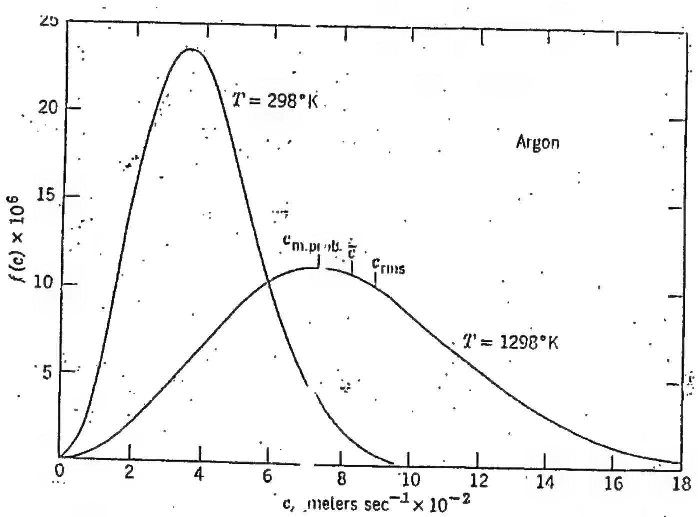
Maxwell distribution of velocity in three dimensions

$$f(v)\,dv = (2/\pi)^{1/2}\,(m/kT)^{3/2}\,v^2 \exp(-mv^2/2kT)\,dv$$

$$\langle v\rangle = (8kT/\pi m)^{1/2} \qquad (\langle v^2\rangle)^{1/2} = (3kT/m)^{1/2} \qquad \Phi = \langle v\rangle^2/\langle v^2\rangle = 8/3\pi = 0.848826$$



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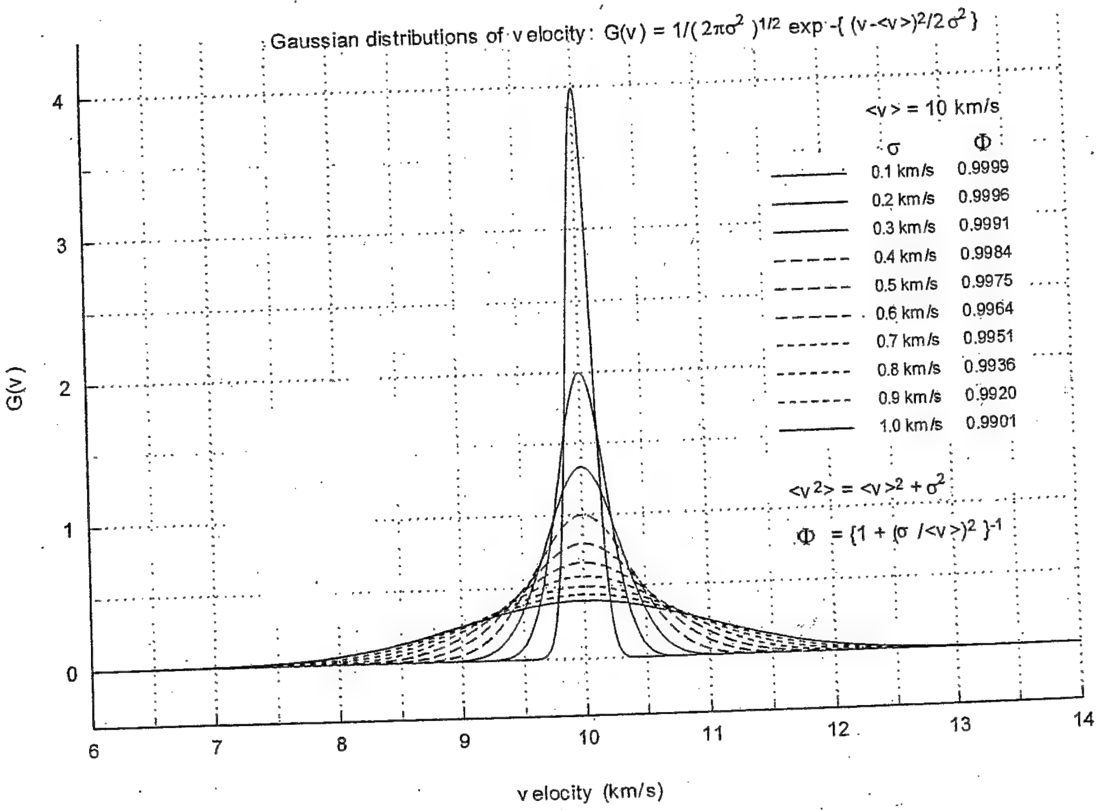

Laser Sustained Plasma Free Jet as a Tool for Propulsion

Proc. First Int'l Symposium on Beamed Energy Propulsion
A.N. Pakhomov, Ed., Am. Inst. Phys., 2003 p.113

A. Lebéhot, M. Dupuy, V. Lago, and M. Dudeck

Laboratoire d'Aérothermique, CNRS
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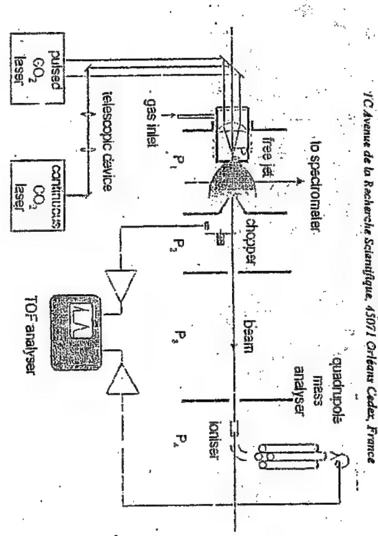
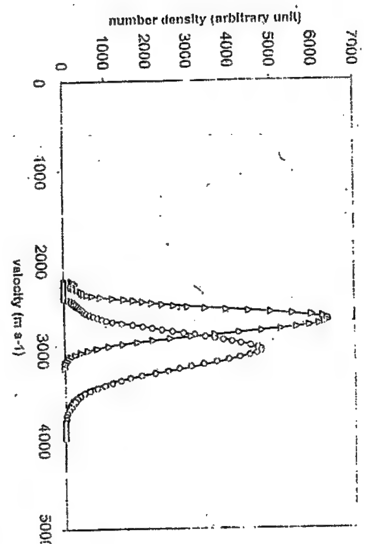


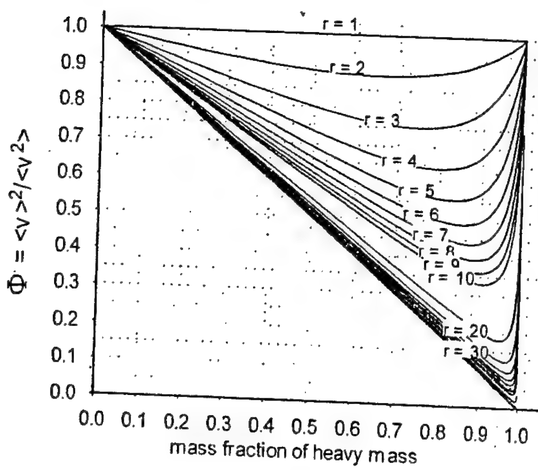


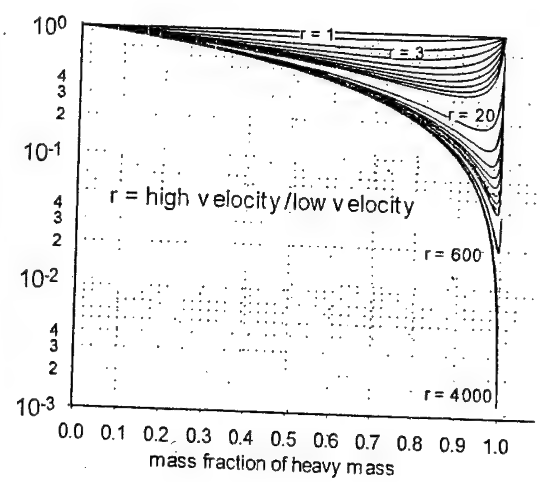
Φ for Bimodal velocity distribution

Chunks of propellant, f_{heavy} mass fraction, v_{slow} velocity
Hot gases, f_{light} mass fraction, v_{fast} velocity

$$\langle v\rangle^2 = (f_{heavy}v_{slow} + f_{light}v_{fast})^2 \qquad \langle v^2\rangle = f_{heavy}v_{slow}^2 + f_{light}v_{fast}^2$$

$$\Phi = \langle v\rangle^2/\langle v^2\rangle = (f_{heavy} + f_{light}r)^2/(f_{heavy} + f_{light}r^2) \text{ where } r = v_{fast}/v_{slow} > 1$$





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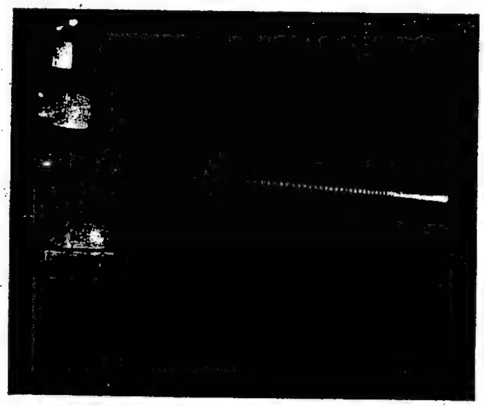

Figure 7. Time exposure of nighttime flight of Myrabo Laser Lightcraft. The time between flashes of the air plasma is 0.04 s.

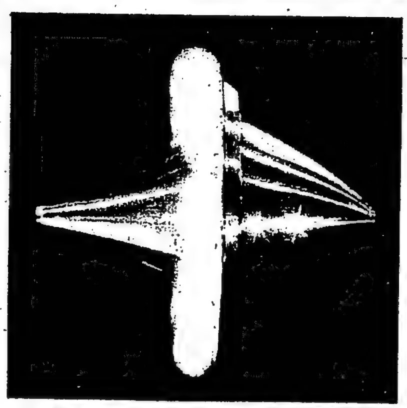

Figure 8. The Myrabo Laser Lightcraft showing air plasma. The Model 200-3/4 is ~0.1 m diameter at largest circumference. The aluminum model weighs ~30 g without Delrin. About 10 g of Delrin was used in the Solid Ablative Rocket (SAR) of which ~0.3 g was ablated during a typical flight with about 100 shots.

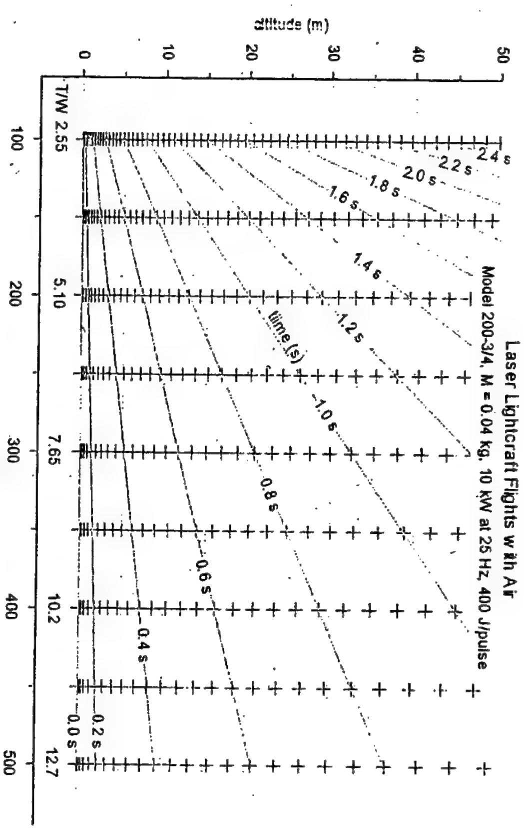

Figure 6. Laser Lightcraft flights with air with various coupling coefficients for a Model 200-3/4 laser Lightcraft, with mass of 40 grams. These flight patterns are also valid for flights with onboard propellant provided that the mass of ablated propellant is much less than the test article mass, $f > 0.99$. T/W = 1 when C_m = 39.2 Ns/MJ.

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Conclusions

When $P_{laser}/m_o \sim 0.05$ MW/kg small payloads (2 to 4 kg) may be launched into low earth orbit, $\Delta v \sim 10{,}000$ m/s.

At the same mass fraction, $f = 0.2$, m/E_{jet} for constant momentum mission is 23% greater than for constant specific impulse mission.

For $\Delta v = 10{,}000$ m/s, $m_o/P_{jet} = 20$ kg/MW, $f = 0.2$, $v_o = 0$, the mission time for constant specific impulse propulsion is ~ 315 sec.

For $\Delta v = 10{,}000$ m/s, $m_o/P_{jet} = 20$ kg/MW, $f = 0.2$, $v_o = 2000$ m/s, the mission time for constant momentum propulsion is ~ 155 sec.

At the same $m/E_{jet} = 0.013$ kg/MJ and Δv, f(constant momentum) = 0.35, and f(constant specific impulse) = 0.20.

Based on measured I, E_L, and ablated mass, overall energy conversion efficiencies (laser energy to jet kinetic energy) of $\alpha\beta \sim 50\%$ were obtained with Delrin propellant in the laser lightcraft.

Jet exit velocities of ~ 2000 m/s with Delrin (based on measured mass) and ~ 3000 m/s with air (based on estimated mass).

THE COUPLING COEFFICIENT AND THE SPECIFIC IMPULSE

$$Q^* = \beta E_L/m$$

$$E_{jet} = \tfrac{1}{2}\, m\langle v^2\rangle = \alpha m Q^* = \alpha\beta E_L$$

$$I = m\langle v\rangle$$

$$C = \frac{I}{E_L}$$

$$\tfrac{1}{2}C\langle v\rangle = \alpha\beta\Phi \le 1$$

$$P_L = \omega E_L$$

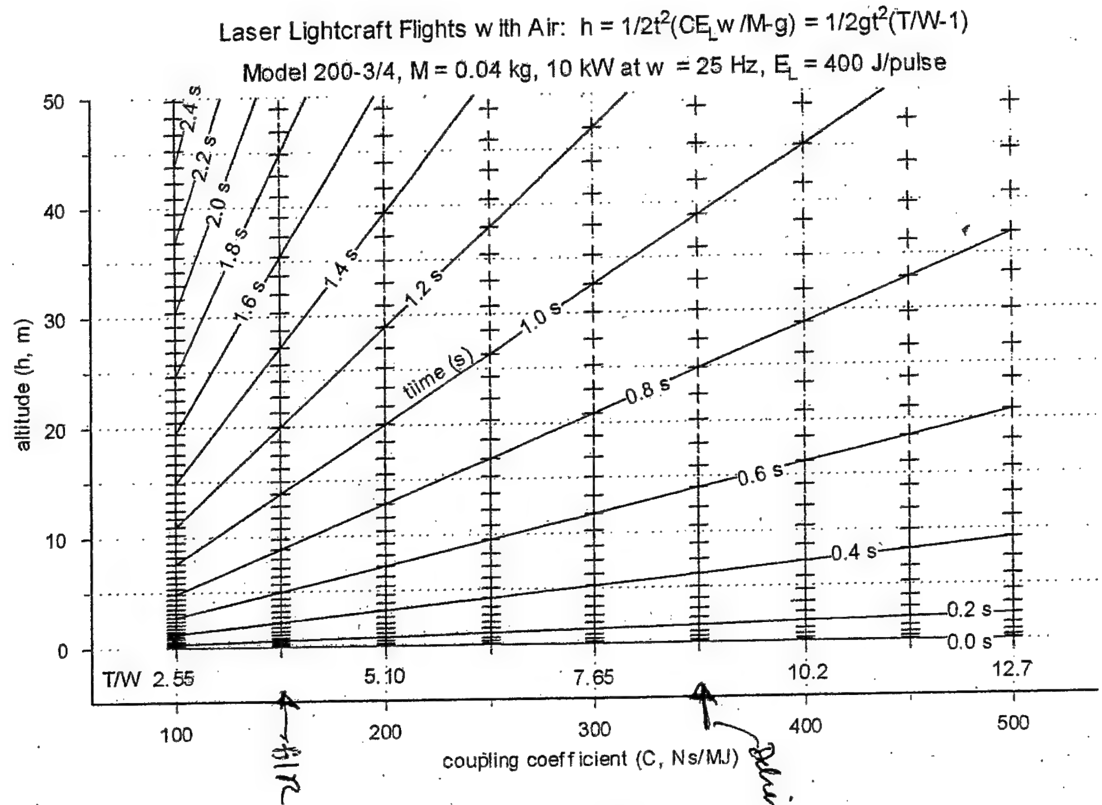
$$F = \omega E_L C$$

$$\tfrac{1}{2}F\langle v\rangle = \alpha\beta\Phi\, P_L$$

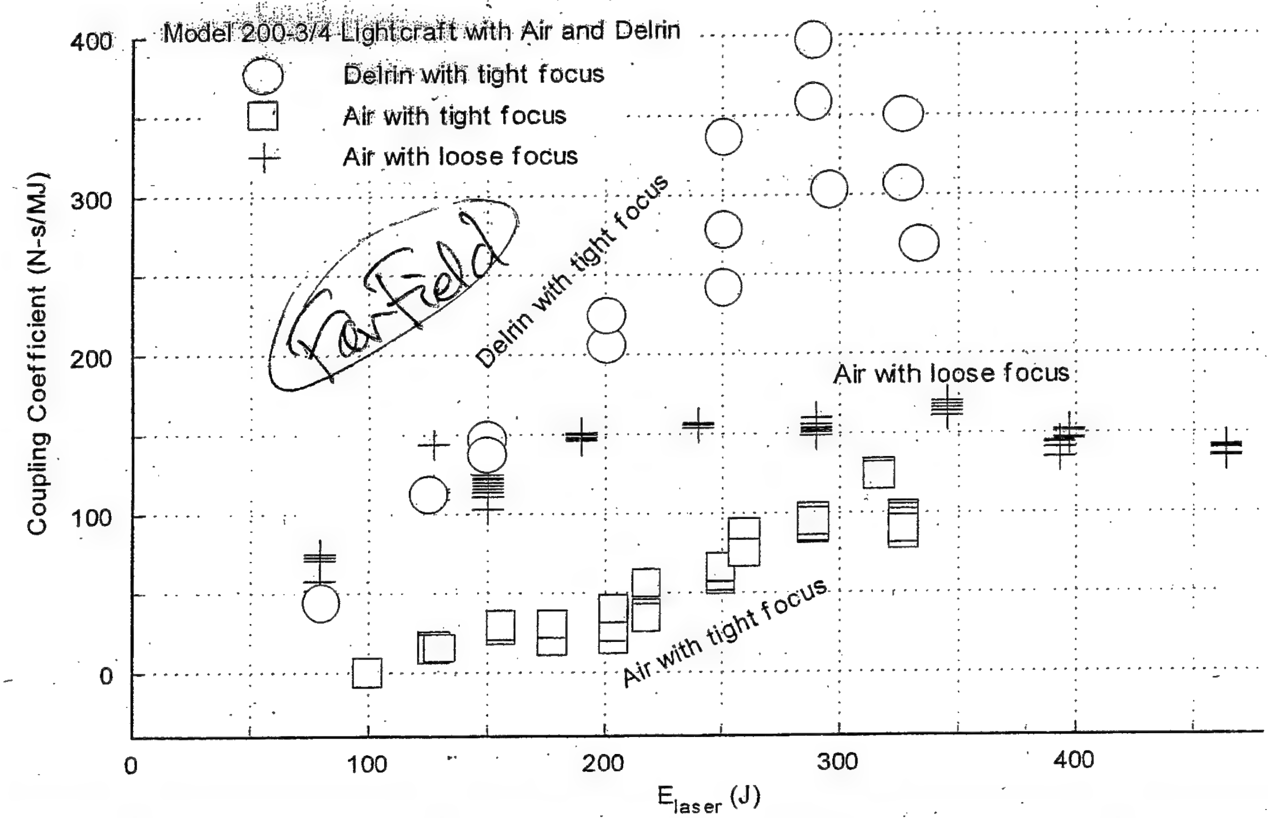
$$P_{jet} = \frac{1}{2}\frac{F\langle v\rangle}{\Phi} = \alpha\beta P_L$$

$$(\alpha\beta\Phi)_{apparent} = \alpha\Phi(\beta + m\Delta u_{chem}/E_L)$$

BACKUP CHARTS



Laser Lightcraft Flights with Air: h = 1/2t²(CE_L w /M-g) = 1/2gt²(T/W-1)
Model 200-3/4, M = 0.04 kg, 10 kW at w = 25 Hz, E_L = 400 J/pulse
altitude (h, m)
coupling coefficient (C, Ns/MJ)
T/W 2.55
5.10
7.65
10.2
12.7
2.4 s
2.2 s
2.0 s
1.8 s
1.6 s
1.4 s
1.2 s
1.0 s
time (s)
0.8 s
0.6 s
0.4 s
0.2 s
0.0 s
Air
Delrin



Model 200-3/4 Lightcraft with Air and Delrin
Delrin with tight focus
Air with tight focus
Air with loose focus
Far Field
Delrin with tight focus
Air with loose focus
Air with tight focus
Coupling Coefficient (N-s/MJ)
E_{laser} (J)

Table 1. Normalized absorption volume for air at 1.18 kg/m^3 as a function of internal energy and laser energy.

u MJ/kg	V_{abs}/β, normalized absorption volume, cm^3 E_L=50 J	E_L=100 J	E_L=150 J	E_L=200 J	E_L=300 J	E_L=400 J
1	42.3	84.7	127.1	169.4	254.2	338.9
2	21.1	42.3	63.5	84.7	127.1	169.4
3	14.1	28.2	42.3	56.5	84.7	112.9
4	10.5	21.1	31.7	42.3	63.5	84.7
5	8.47	16.9	25.4	33.9	50.8	67.8
6	7.06	14.1	21.1	28.2	42.3	56.5
7	6.05	12.1	18.1	24.2	36.3	48.4
8	5.30	10.5	15.8	21.1	31.7	42.3
9	4.71	9.42	14.1	18.8	28.2	37.6
10	4.24	8.47	12.7	16.9	25.4	33.9
15	2.82	5.65	8.47	11.3	16.9	22.6
20	2.12	4.24	6.36	8.47	12.7	16.9
30	1.41	2.82	4.24	5.65	8.47	11.3
40	1.06	2.12	3.18	4.24	6.36	8.47
50	0.85	1.69	2.54	3.39	5.08	6.78
60	0.71	1.41	2.12	2.82	4.24	5.65
70	0.61	1.21	1.82	2.42	3.63	4.84
80	0.53	1.06	1.59	2.12	3.18	4.24
90	0.47	0.94	1.41	1.88	2.82	3.77
100	0.42	0.85	1.27	1.69	2.54	3.39
110	0.39	0.77	1.16	1.54	2.31	3.08

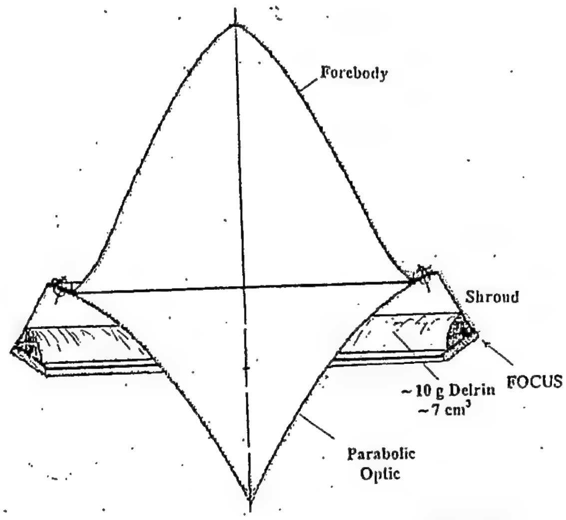


Figure 1. Cross-sectional view of Myrabo Laser Lightcraft, Model 200-3/4. The maximum diameter of the test article at the shroud is ~ 10 cm. The indicated ring of Delrin weighs ~ 10 g and has a volume of ~ 7 cm^3 and a surface area ~ 25 cm^2. The idealized plug nozzle exit area is ~ 350 cm^2.

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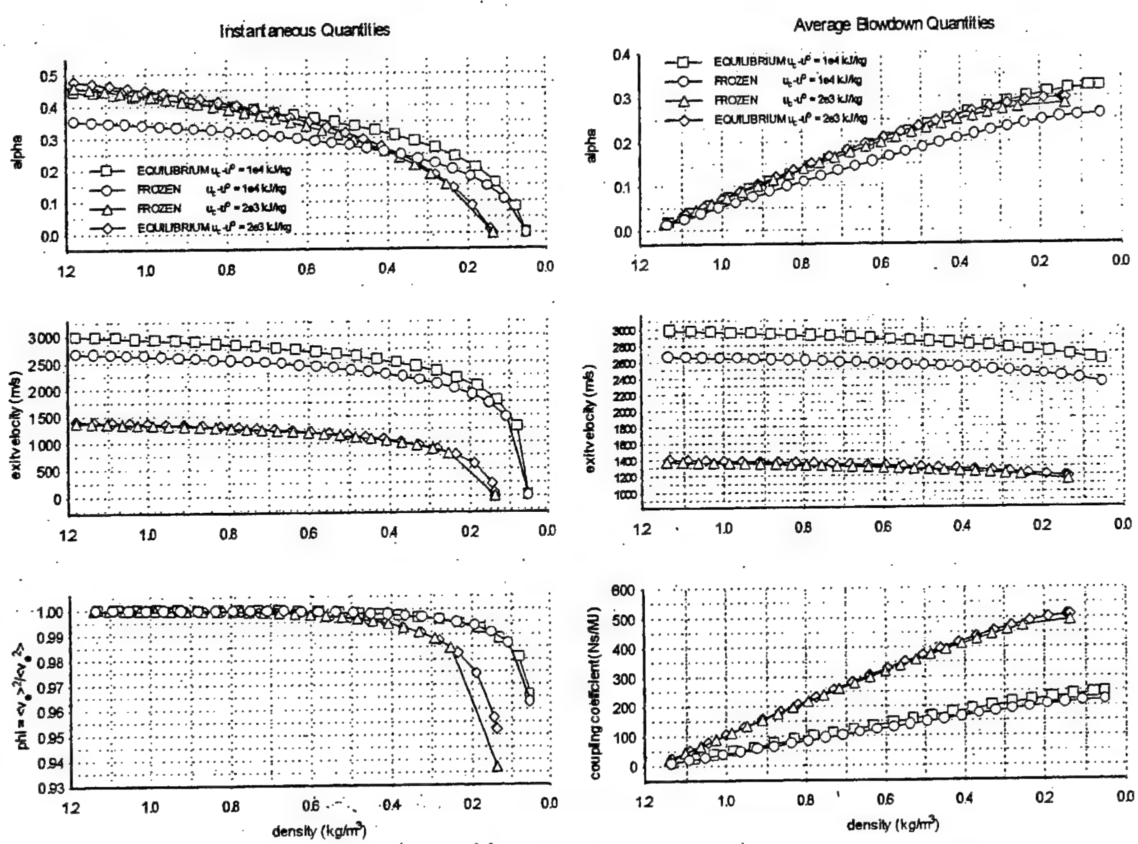

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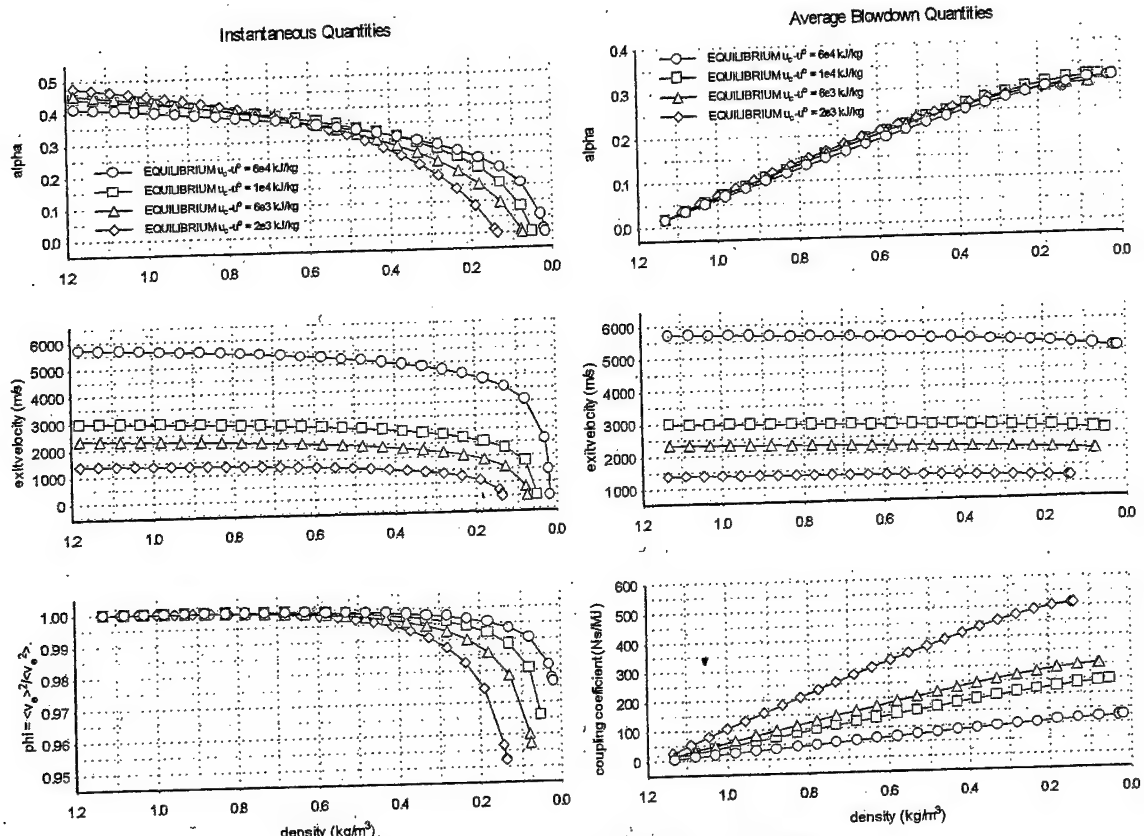

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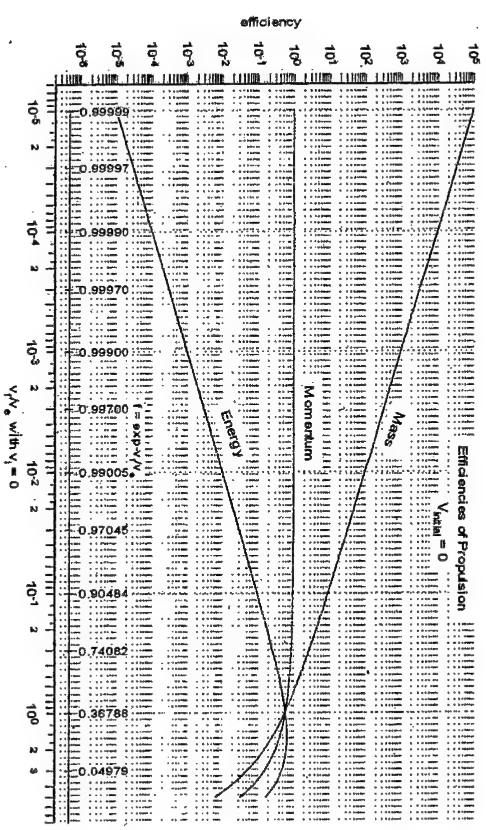

Figure 2a. Propulsion efficiencies for missions with zero initial velocity.

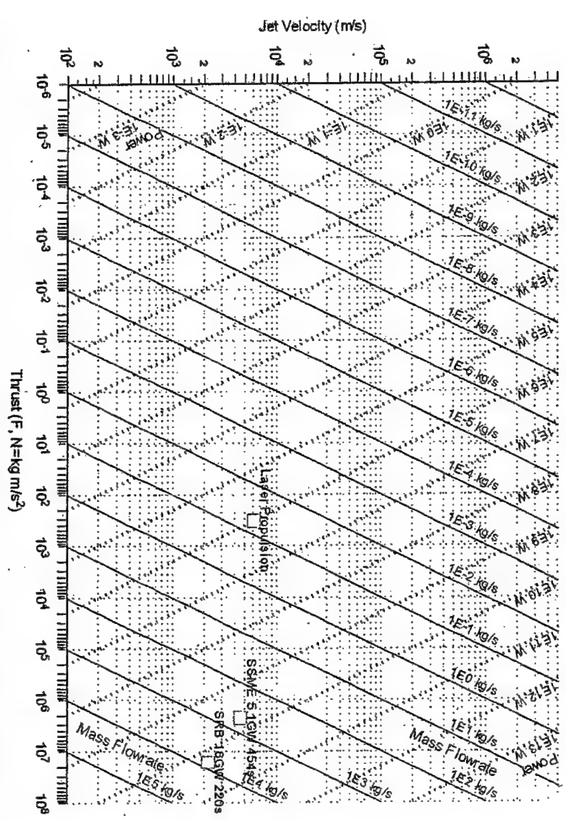

Figure 1. Parameter space for rockets: $F = v_e\, dm/dt$, and P (power) $= \frac{1}{2}\, dm/dt\, v_e^2$.

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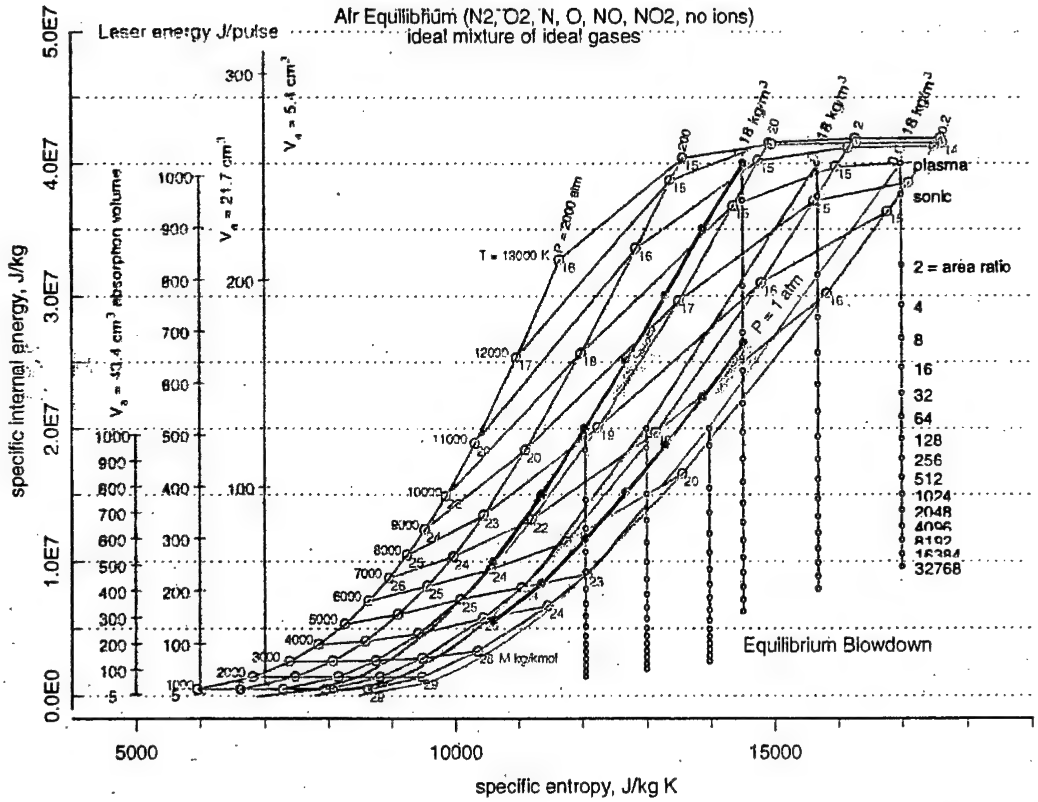

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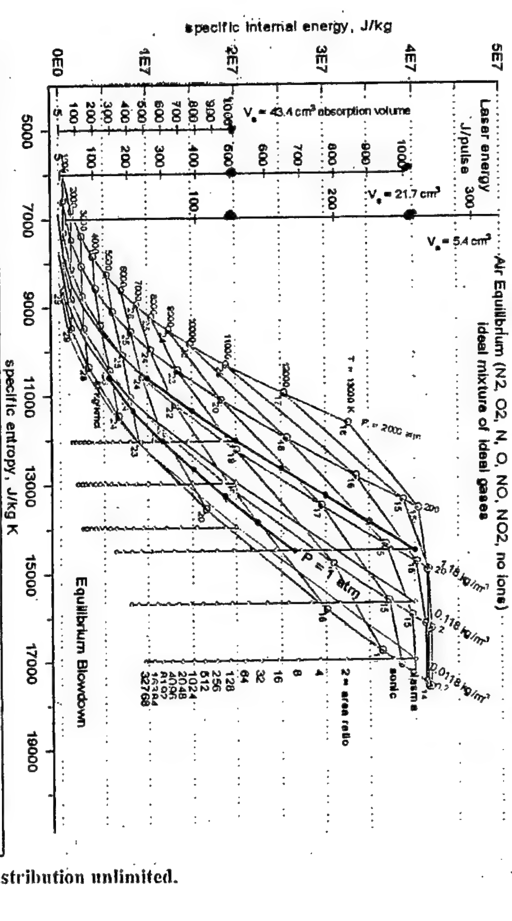


Figure 15. Mollier diagram for equilibrium air without ions. Numbers adjacent to intersections of isobars and isotherms indicate average molecular weight. Upper heavy line is a constant density = 1.18 kg/m³ line. three isentropes from u = 4e7 and 2e7 J/kg represent equilibrium blowdown for the indicated area ratios, 1 to 32768. The P = 1 atm isobar is reached with an area ratio ~ 8 from the initial u = 4e7 and ~ 4 from the u = 2e7 J/kg state, respectively. The exit velocities from these two expansions are ~ 5000 and 3000 m/s, respectively.

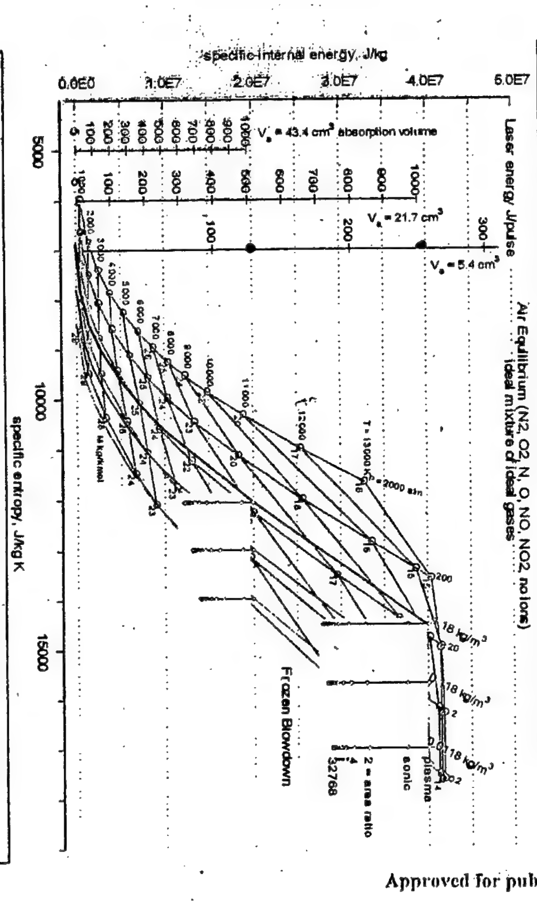
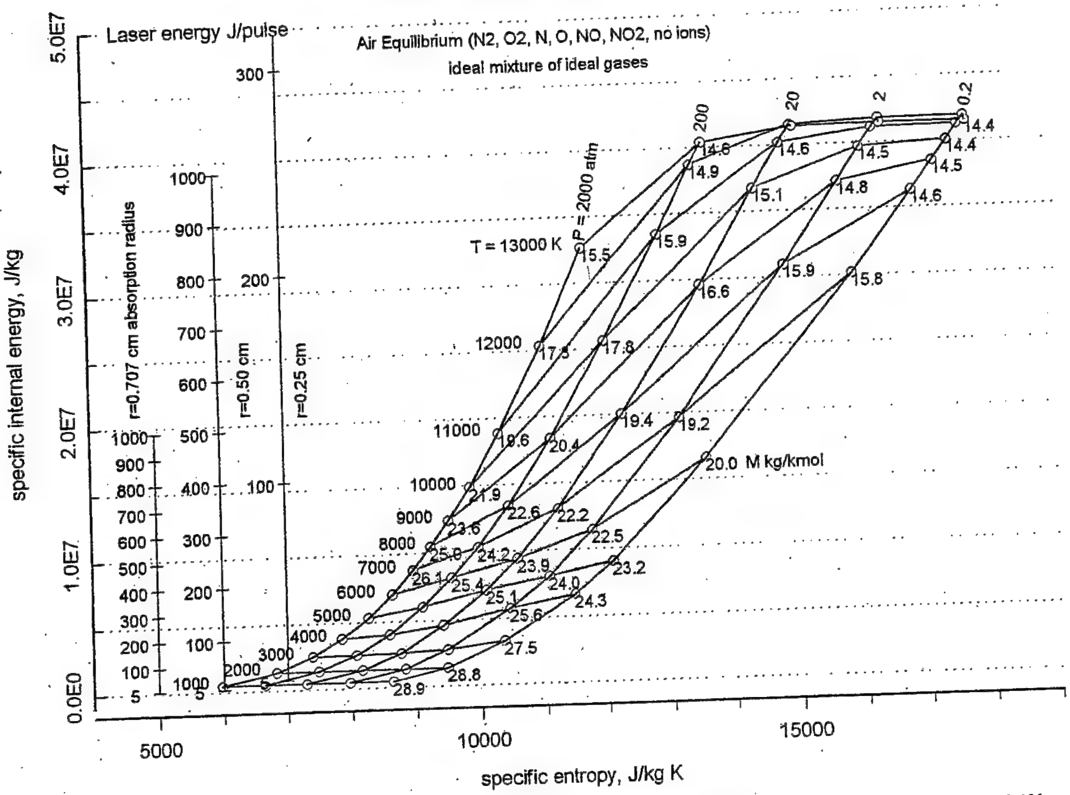


Figure 16. Process representations of air expansion with frozen blowdown, as in Figure 15. The frozen isentropic expansions from u = 4e7 and 2e7 J/kg and 1.18 kg/m3 to 1 atm produce exit velocities of 5000 and 3000 m/s, respectively.



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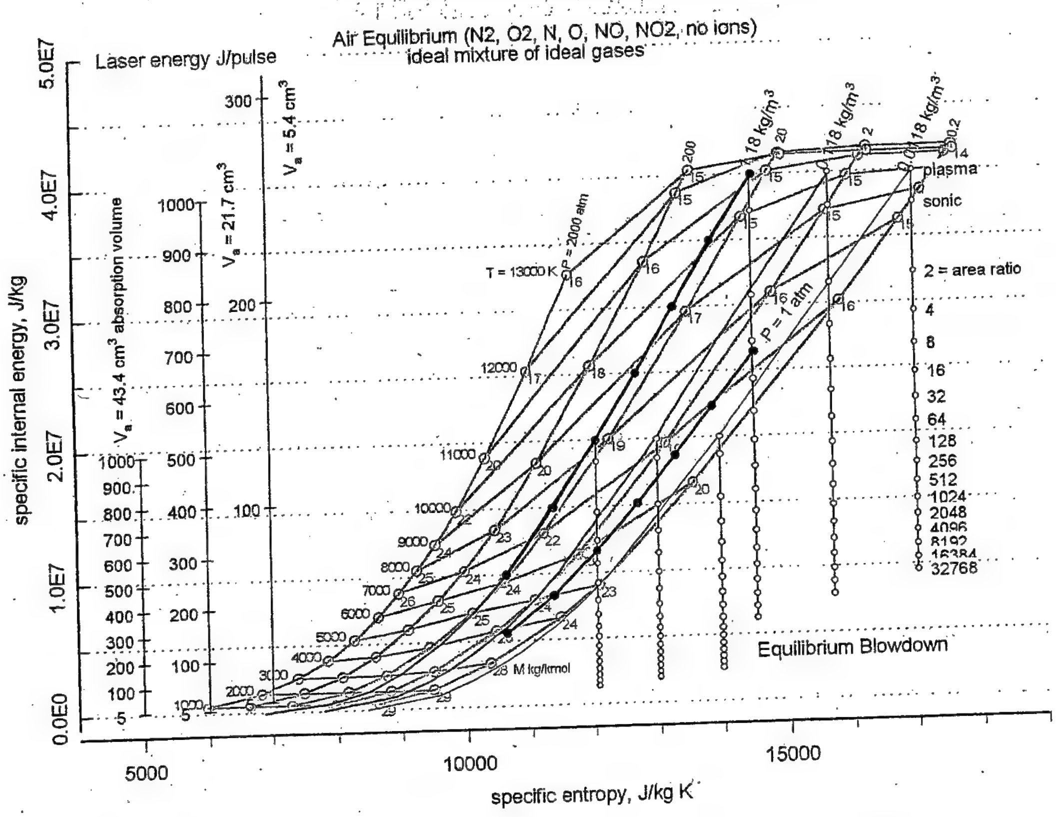

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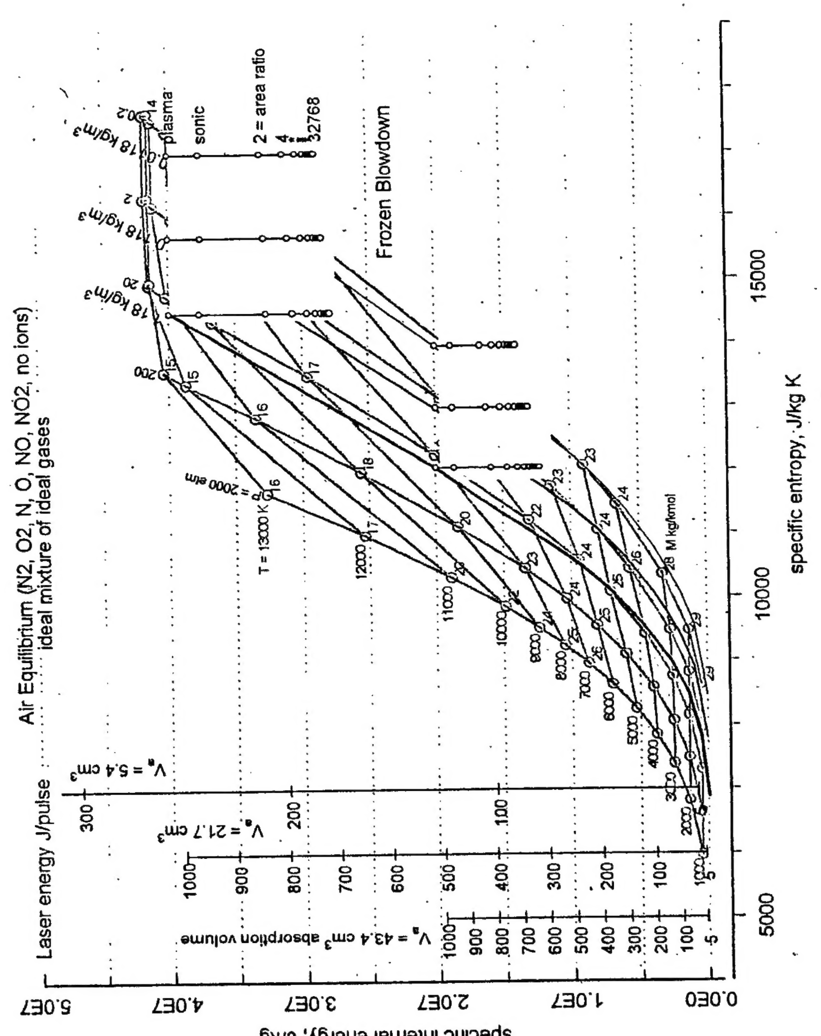

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Thermodynamic properties of equilibrium air,
$\rho = 1.18$ kg/m^3.

u	T	P	h	s	c_p	M_m	$X(e^-)$	v_a	c_p/c_v
MJ/kg	10^3 K	bar	MJ/kg	KJ/kg K	KJ/kg K	kg/kmol		km/s	
-0.9	0.298	1.00	0	6.864	1.005	28.965	0	0.35	1.40
1	1.6	5.4	1.5	8.2	1.25	29.0	4E-10	0.77	1.30
2	2.5	8.6	2.7	8.7	1.51	28.9	3.E-09	0.95	1.24
3	3.2	11.1	3.9	9.0	2.16	28.6	3.E-08	1.06	1.20
4	3.7	13.1	5.1	9.3	2.83	27.8	3.E-07	1.15	1.19
5	4.1	15.0	6.3	9.6	3.15	26.9	2.E-06	1.23	1.19
6	4.5	16.9	7.4	9.8	3.04	26.1	5.E-06	1.32	1.21
7	4.9	19.1	8.6	10.0	2.69	25.3	2.E-05	1.41	1.23
8	5.4	21.5	9.8	10.2	2.56	24.7	4.E-05	1.50	1.23
9	5.9	23.9	11.0	10.4	2.86	24.2	8.E-05	1.57	1.21
10	6.3	26.0	12.2	10.6	3.43	23.8	1.E-04	1.62	1.19
15	7.5	34.1	17.9	11.3	6.70	21.7	5.E-04	1.84	1.17
20	8.3	41.3	23.5	11.9	8.93	19.8	9.E-04	2.02	1.17
30	9.7	56.2	34.8	13.0	9.09	16.9	3.E-03	2.38	1.19
40	11.5	75.4	46.4	14.0	5.13	15.0	1.E-02	2.81	1.24
50	14.4	101	58.5	14.8	4.81	14.0	4.E-02	3.26	1.25
60	16.6	124	70.5	15.4	6.62	13.2	1.E-01	3.60	1.24
70	18.4	145	82.3	16.0	8.25	12.4	1.E-01	3.91	1.24
80	19.9	167	94.1	16.5	9.51	11.7	2.E-01	4.20	1.24
90	21.3	189	106.0	17.0	10.40	11.1	2.E-01	4.48	1.25
100	22.6	211	118.0	17.4	10.90	10.5	3.E-01	4.76	1.26
110	23.9	235	130.0	17.9	11.10	10.0	3.E-01	5.03	1.27

Thermodynamic properties of Mach 5 air at stagnation density,

$\rho = 5.90$ kg/m^3.

u	T	P	h	s	c_p	M	X(e$^-$)	v_a	c_p/c_v
MJ/kg	10^3 K	bar	MJ/kg	KJ/kg K	KJ/kg K	kg/kmol		km/s	
0.102	0.560	9.492	0.263	6.864	1.042	28.965	0	0.471	1.38
1	1.6	27.1	1.5	7.7	1.25	28.97	4e-13	0.77	1.30
2	2.6	43.2	2.7	8.2	1.45	28.95	6.E-11	0.96	1.25
3	3.3	56.5	4.0	8.6	1.85	28.73	2.E-08	1.08	1.21
4	3.9	67.7	5.1	8.9	2.33	28.19	3.E-07	1.17	1.20
5	4.4	78.2	6.3	9.1	2.65	27.46	2.E-06	1.26	1.20
6	4.8	88.9	7.5	9.3	2.71	26.69	6.E-06	1.35	1.22
7	5.3	100.3	8.7	9.5	2.61	25.96	2.E-05	1.45	1.23
8	5.8	112.4	9.9	9.7	2.55	25.32	4.E-05	1.53	1.23
9	6.3	124.5	11.1	9.9	2.69	24.79	8.E-05	1.61	1.22
10	6.7	135.8	12.3	10.0	3.04	24.32	1.E-04	1.67	1.21
15	8.2	182.0	18.1	10.7	5.49	22.19	6.E-04	1.91	1.18
20	9.2	222.3	23.8	11.2	7.36	20.32	1.E-03	2.11	1.18
30	10.8	304.9	35.2	12.2	8.05	17.41	3.E-03	2.49	1.20
40	12.7	404.9	46.9	13.1	5.52	15.45	1.E-02	2.92	1.24
50	15.6	534.8	59.1	13.8	4.28	14.33	3.E-02	3.39	1.27
60	18.4	667.9	71.3	14.4	5.20	13.54	8.E-02	3.78	1.26
70	20.8	794.6	83.5	14.9	6.32	12.81	1.E-01	4.13	1.27
80	22.8	919.9	95.6	15.4	7.26	12.14	2.E-01	4.45	1.27
90	24.6	1046.6	107.7	15.8	7.99	11.52	2.E-01	4.76	1.28

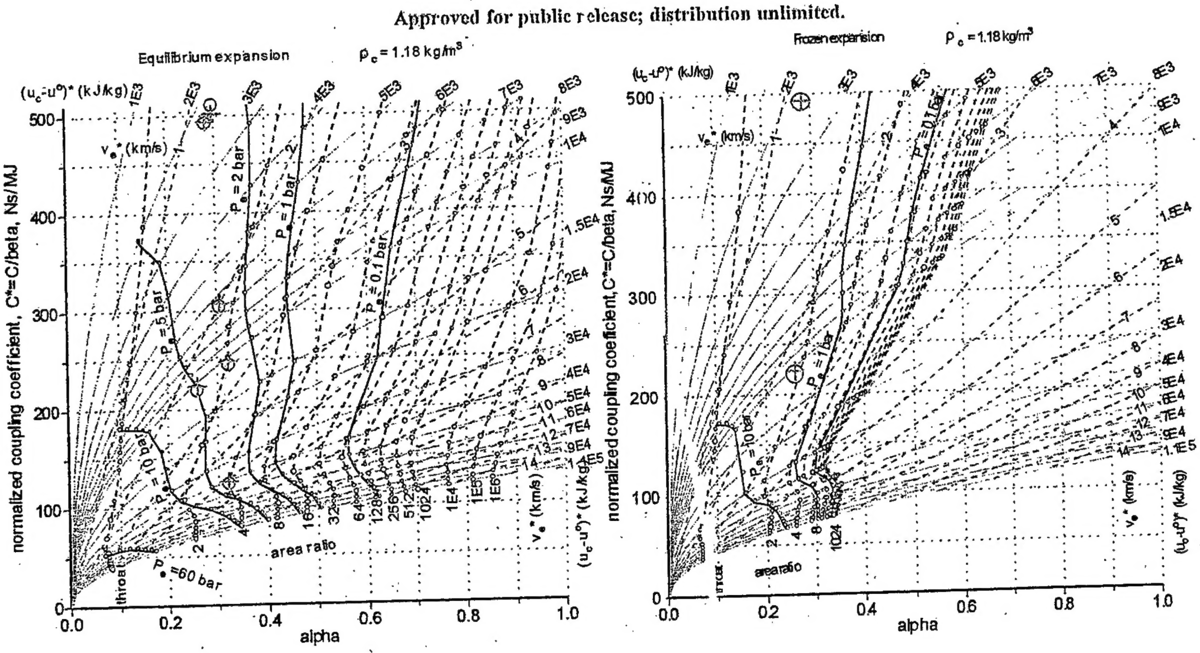

Figure 10. Comparison of Equilibrium expansion and frozen expansion of air. The circles and nearby crosses represent the blowdown quantities obtained from initial $[u_c\text{-}u^o]^*$ states of 2E3, and 1E4 J/kg for the frozen expansion and 2E3, 6E3, 1E4, and 4E4 kJ/kg for the equilibrium expansion. The results of the two frozen blowdown integrations to P_{exit} = 1 bar are plotted with those of the equilibrium blowdown to show that the differences in alpha are small, i.e., at low energy (2E3) 0.30 and 0.29 and at high energy (1E4) 0.32 and 0.27 for equilibrium and frozen blowdown, respectively.

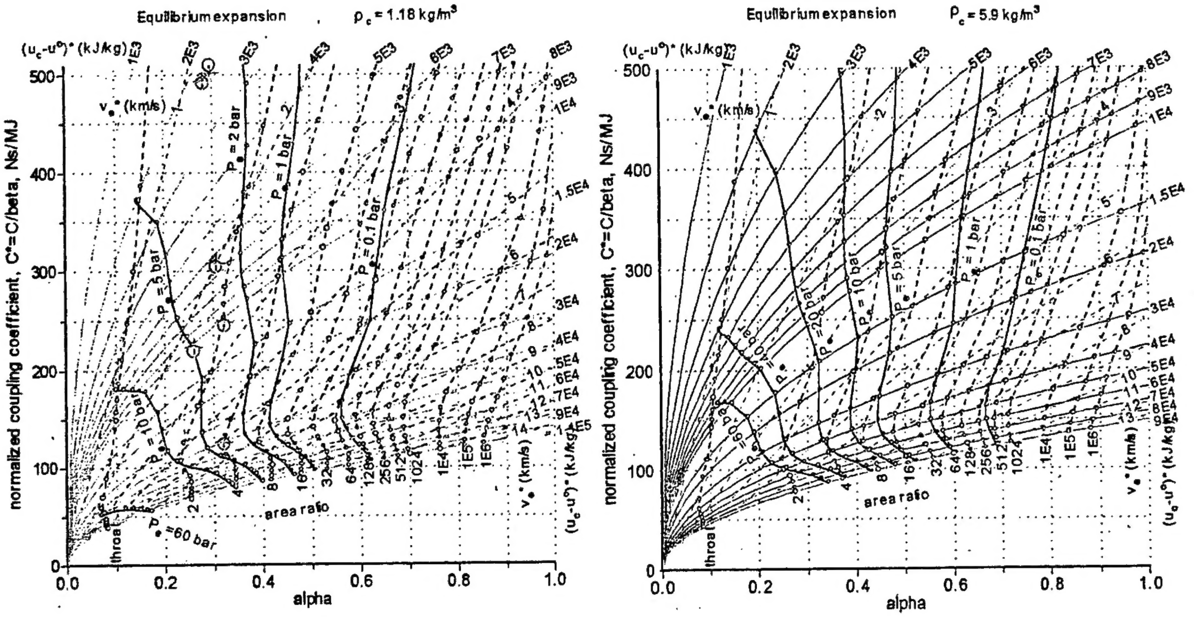

Figure 11. Comparison of Equilibrium expansion from laser heated STP air (1.18 kg/m³) and Mach 5 air at stagnation density (5.9 kg/m³). In the STP air diagram (on left), the circles and nearby crosses represent the blowdown quantities obtained from initial $[u_c-u^o]^*$ states of 2E3, and 1E4 J/kg for the frozen expansion and 2E3, 6E3, 1E4, and 4E4 kJ/kg for the equilibrium expansion.

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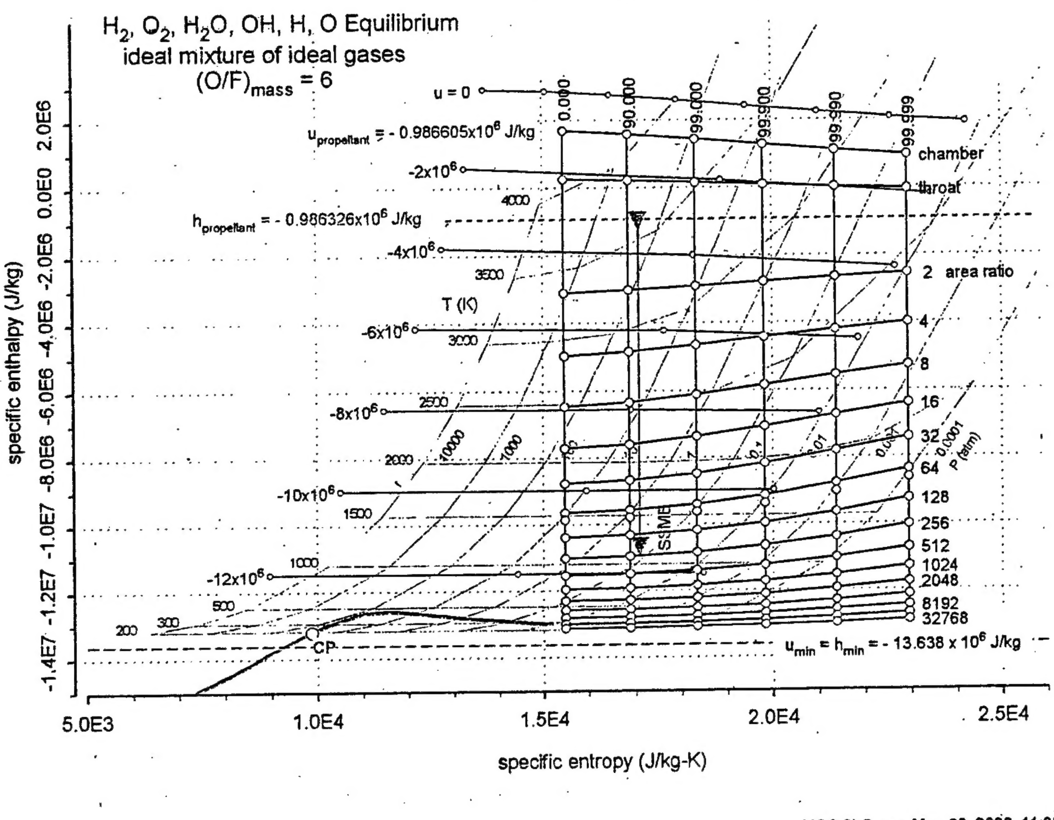

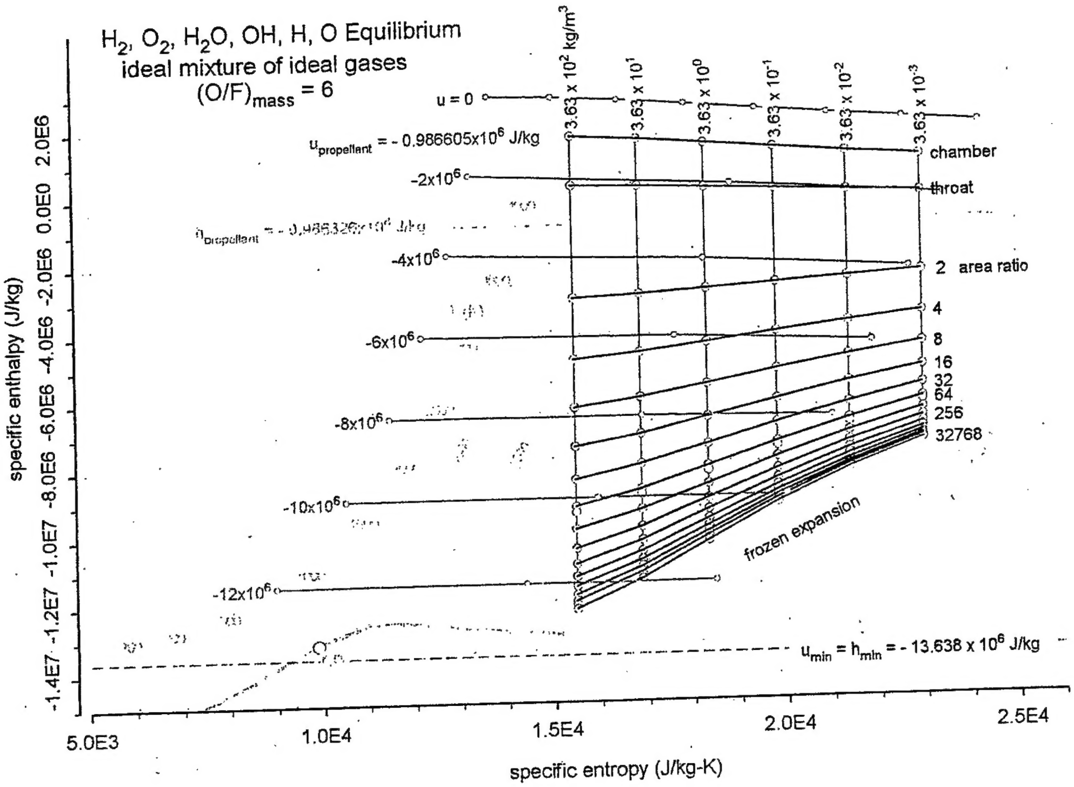

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